

Design and investigation of a 15-kVAR reactive power compensation unit for different load changes

Abstract. Reactive Power Compensation Units (RPCUs) are used to supply reactive power for inductive loads. Reactive power is consumed by inductive loads such as electric motors, transformers etc. In this study, a 15-kVAR RPCU was investigated for different load changes. RPCU consists of capacitor equipment in eight stages. To investigate the RPCU, an inductive load bank, a resistive load bank, and an asynchronous motor were used. At the end of the study, a performance analysis of the RPCU was performed for load changes under different conditions.

Streszczenie. W artykule przedstawiono wyniki badań równoległego kompensatora mocy biernej (ang. Reactive Power Compensation Unit) opartego na ośmiostopniowej baterii kondensatorów o mocy 15kVAR w warunkach zmiennego obciążenia. W testach wykorzystano zespół dławików, rezystorów oraz maszynę asynchroniczną. (**Badania kompensatora mocy biernej o mocy 15kVAR w warunkach zmiennego obciążenia**)

Keywords: reactive power, compensation, reactive power relay, load changes.

Słowa kluczowe: Moc bierna, kompensacja, zmiany obciążenia, generacja mocy biernej.

Introduction

The term compensation is used to describe the intentional insertion of reactive power devices, capacitive or inductive, into a power network to achieve a desired effect [1]. This may include improved voltage profiles, improved power factor, enhanced stability performance, and improved transmission capacity [1].

Reactive power is tightly related to bus voltages throughout a power network, and hence it has a significant effect on system security [2]. One of the main reasons for some of the recent major blackouts in the power systems around the world such as those occurred in September 23, 2003 in Sweden and Denmark, September 28, 2003 in Italy and also the United State and Canada blackout (August 2003) was reported as the insufficient reactive power of system resulting in the voltage collapse [2] – [5].

Reactive power compensation units are used to supply reactive power requirement for inductive loads such as motors, transformers, etc. Inductive loads have wide area on energy consuming. More than 60% of the total electrical energy is consumed by electric motors [6], [7].

Power quality conditioners compensate reactive power requirement [8], [9]. To maintain the controlled power quality regulations, some kind of compensation at all the power levels is becoming a common practice [10] – [15].

Reactive power compensation at load side is very important because it minimizes the transmission loss [16] – [24]. For example, in periods when there is no sun-shine, the inverter on a photovoltaic system supplies the network with reactive power only [25]. If there is no compensation unit constructed for photovoltaic system, there will be occurred transmission loss on electric grid.

To achieve compensation process, some reactive equipment is connected to the load terminals in series or in parallel.

Compensation with series capacitors is shown in Fig. 1. Series capacitors are utilized to neutralize part of the inductive reactance of a power network [1].

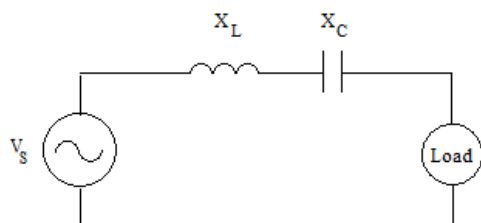


Fig.1. Circuit with series capacitor

Shunt capacitors may be considered instead of series capacitors because of series capacitors are of little value when the reactive power requirements of the load are small, in cases where thermal considerations limit the line current, series capacitors are of little value since the reduction in line current associated with them is relatively small [1].

The proper reactive power compensation by shunt capacitors can achieve the best-cost benefit if the reduction of peak load demand and energy consumption over the life cycle of capacitors is considered [26], [27].

Reactive power requirement of inductive loads is supplied by shunt capacitors. To achieve this, some capacitor equipment is connected to the load terminals in parallel. The reactive power requirement is called capacitive reactive power. Capacitors may either be energized continuously or switched on and off during load cycles [1]. A sample shunt compensation unit is shown in Fig. 2.

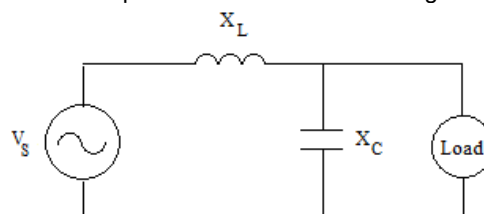


Fig.2. Shunt compensation

In this study, a reactive power compensation unit (RPCU) with shunt capacitors was examined. This unit has approximately a 15-kVAR capacitors group which is connected to electric network in parallel. The compensation unit was studied under some loads such as a resistive load bank, an inductive load bank, and an asynchronous motor.

Reactive power compensation unit

A 15-kVAR RPCU is shown in Fig. 3. As shown in Fig. 3, the RPCU consists of miniature circuit breakers (MCBs), contactors, harmonic filters (reactors), and capacitors. MCBs turn off or on each capacitor unit for manually. Contactors are controlled by a reactive power control relay (RPCR) in electronically. To supply reactive power requirement, each capacitor are linked to the network by RPCR. Harmonic filters neutralize harmonics in RPCU.

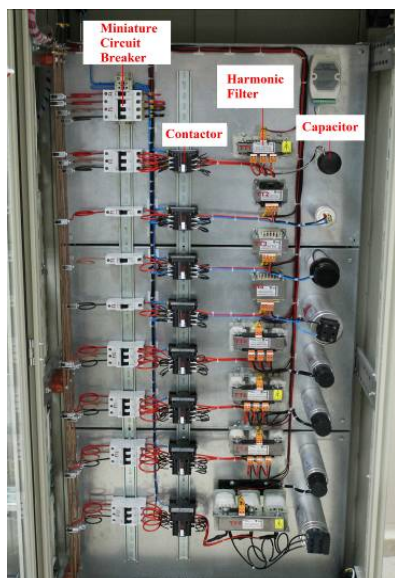


Fig.3. Reactive power compensation unit

In Fig. 4, capacitor stages in RPCU are illustrated. As shown in Fig. 3 and 4 respectively, there are eight stages for compensation process. Each stage is linked to the line bus in parallel. Whole capacitors in the system are operated in automatically by a reactive power control relay. To eliminate some harmonic effects, harmonic filters (reactors) are connected to capacitors in series (Fig. 4). There are 3-phase and 1-phase capacitors in RPCU.

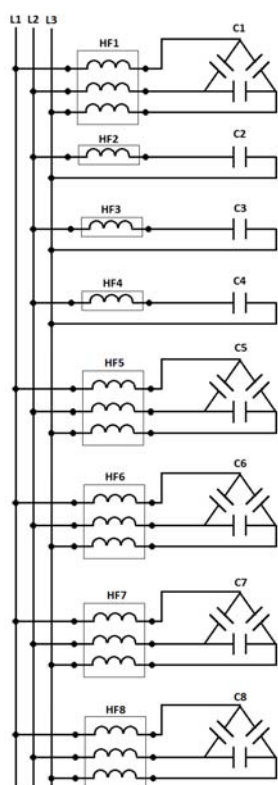


Fig.4. Capacitor stages

Some specifications about capacitor equipment are shown in Tab. 1. Each capacitor is linked on the power line to supply reactive power requirement by RPCR automatically.

Table 1. Capacitor specifications

Stage	Voltage [V]	Capacitive power [kVAR] / capacitance [μ F]
1	400	0.5 / 3x33.2
2	230	0.55 / 1x33.2
3	230	1 / 1x60.2
4	230	2.5 / 1x75.25
5	400	1 / 3x6.63
6	400	1.5 / 3x9.95
7	400	2.5 / 3x16.6
8	400	5 / 3x33

Experimental study

As shown in Fig. 5, to achieve experimental study, three different load units were examined. These are;

- A resistive load bank (3 x 2.5 kW, 3-phase, star connected),
- An inductive load bank (3 x 3 kVAR, 3-phase, star connected),
- An asynchronous machine (3-phase, 2.2 kW, star connected).



(a)



(b)



(c)

Fig. 5. Loads (a) Resistive load bank, b) Inductive load bank, c) Asynchronous motor)

Load specifications are shown in Tab. 2. Resistive and inductive load banks can be linked to the power line in 3-phase or 1-phase. Each load bank is controlled stage by stage. For example, 3 x 2.5 (3-phase) resistive load bank has 5 stages with 5 x 500W for each phase line. Besides, each phase line of inductive load bank is controlled automatically.

Table 2. Load specifications

Load type	Rating values
Resistive Load Bank	3-phase, 3x2.5 kW (5X500W)
Inductive Load Bank	3-phase, 3x3 kVAR
Asynchronous Motor	3-phase, 380-420 V (Y), 50 Hz, 1430 min ⁻¹ , 2.2 kW, 5.0 A, cos ϕ 0.81, IP55

The experimental set up is shown in Fig. 6. To achieve all measurements, a Fluke 435 power quality analyzer was used. Fluke 435 can measure voltage, current, power, energy demand, harmonics, sags, swells, and other electrical quantities [28].



Fig.6. Experimental set up

First of all, a 8.6 kVAR inductive load unit was connected to the bus line. In this situation, there was no RPCU. For this condition, voltage waveforms are shown in Fig. 7. All data were collected by Fluke 435 power quality analyzer.

Voltage levels were measured as 229.5 V, 232.9 V, and 235.4 V for L1, L2, and L3 power lines respectively. Power factor of the system ($\cos \varphi$) was measured as 0.11.

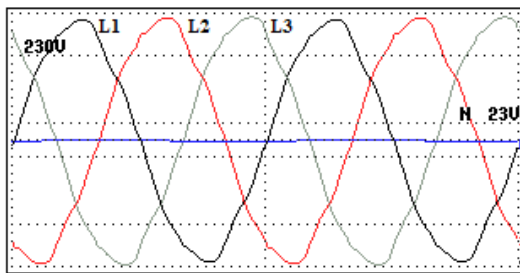


Fig.7. Voltage waveforms from system bus under no compensation condition (for 8.6 kVAR inductive load)

In Fig. 8, current waveforms are shown. Current levels are measured by Fluke 435 as 12 A, 14 A, and 11 A for L1, L2, and L3 respectively. To study this condition, a 8.6 kVAR inductive load unit was connected to the bus line. In this situation, there was no RPCU.

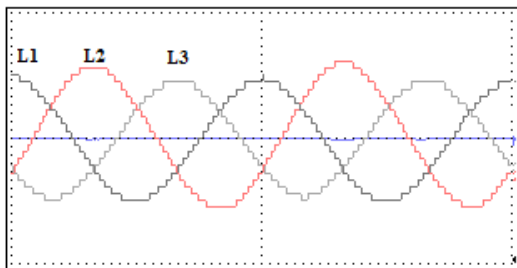


Fig.8. Current waveforms from system bus under no compensation condition (for 8.6 kVAR inductive load)

In Fig. 9, voltage harmonics are illustrated for the 8.6 kVAR inductive load without RPCU. In this figure, there are negligible voltage harmonics as 5th, 7th, and 9th harmonics (250 Hz, 350 Hz, and 450 Hz respectively). The total harmonic distortion (THD) was measured as 4% for this condition.

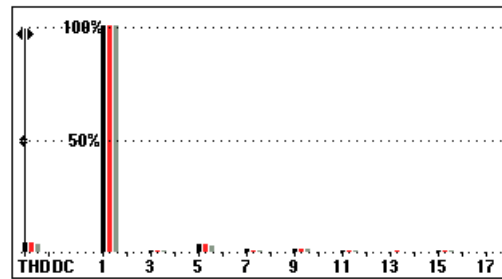


Fig.9. Voltage harmonics from system bus under no compensation condition (for 8.6 kVAR inductive load)

In Fig. 10, current harmonics are shown for 8.6 kVAR inductive load without RPCU. In this figure, there is no significant current harmonic. The THD was measured as 2.2%. Under compensation condition, voltage waveforms are shown in Fig. 11 for the 8.6 kVAR inductive load. Voltage levels were measured as 229.6 V, 232.5 V, and 234.4 V for L1, L2, and L3 respectively. Power factor of the system ($\cos \varphi$) was measured as 0.86. In Fig. 12, current waveforms are shown under compensation condition. Current levels were measured as 3 A, 2.9 A, and 3 A for phase lines L1, L2, and L3 respectively. To study this condition, a 8.6 kVAR inductive load unit was connected to the bus line. In this situation, the RPCU was linked.

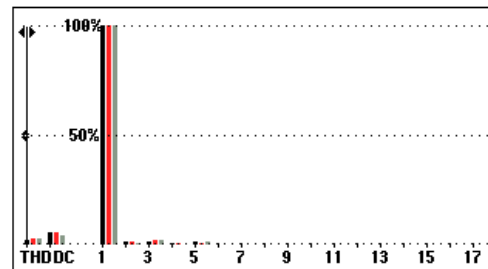


Fig.10. Current harmonic measurement from system bus under no compensation condition (for 8.6 kVAR inductive load)

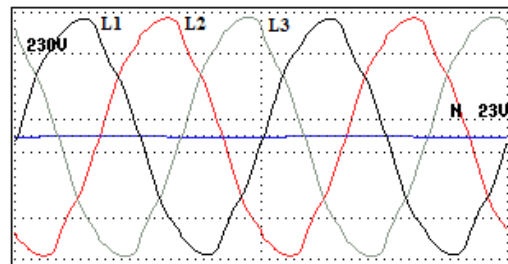


Fig.11. Voltage waveforms from system bus under compensation condition (for 8.6 kVAR inductive load)

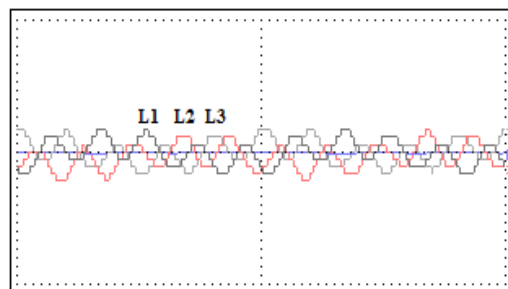


Fig.12. Current waveforms from system bus under compensation condition (for 8.6 kVAR inductive load)

In Fig. 13, voltage harmonics are illustrated for the 8.6 kVAR inductive load with RPCU. The THD was measured as 3.9% for this condition.

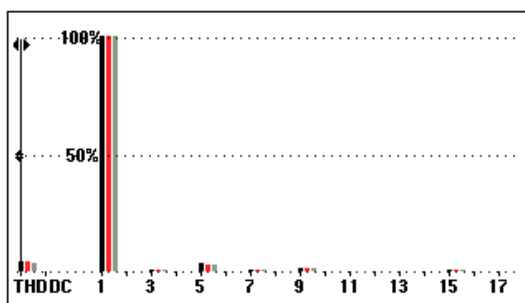


Fig.13. Voltage harmonics from system bus under compensation condition (for 8.6 kVAR inductive load)

In Fig. 14, current harmonics are illustrated for the 8.6 kVAR inductive load with RPCU. In this figure, there are significant current harmonics as 3th, 5th, and 7th. The THD was measured as 172.9% by Fluke 435 power quality analyzer. Those harmonics will be eliminated with another designed harmonic filter in further studies.

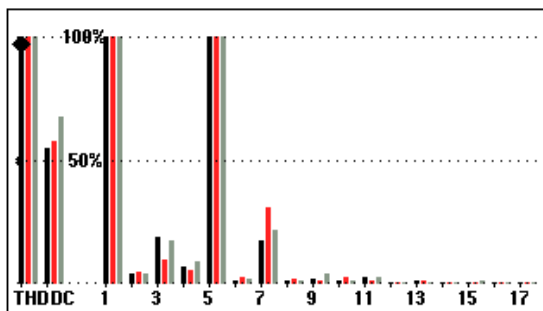


Fig.14. Current harmonic measurements from system bus under compensation condition (for 8.6 kVAR inductive load)

In Fig. 15, voltage waveforms are shown. Voltage levels were measured by Fluke 435 power quality analyzer as 228.5 V, 231.4 V, and 233.6 V for L1, L2, and L3 respectively. To study this condition, a combined load unit which has 8.6 kVAR inductive load and 3 kW (3 x 1 kW) resistive load was connected to the bus line under compensation condition. Power factor of the system ($\cos \phi$) was measured as 0.84 by Fluke 435 power quality analyzer.

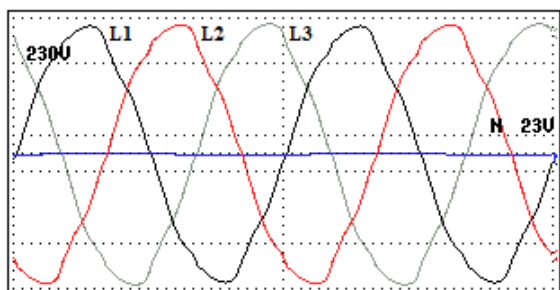


Fig.15. Current waveforms from system bus under compensation (for combined load; 8.6 kVAR inductive and 3 kW resistive)

In Fig. 16, current waveforms are shown for combined load. Current levels were measured by Fluke 435 power quality analyzer as 8 A, 8 A, and 7 A for L1, L2, and L3 respectively.

phase lines respectively. In this situation, the main switch of the RPCU was turned on.

As shown in this figure, current waveforms have some distortions. The current waveforms can be affected by some harmonic sources such as cooling fans of load banks. In this system, there are cooling fans to cool the inductive load bank, the resistive load bank, and the power distribution box.

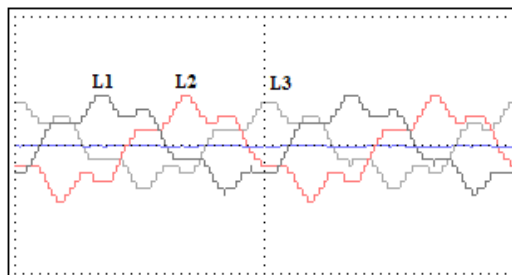


Fig.16. Current waveforms from system bus under compensation (for combined load; 8.6 kVAR inductive and 3 kW resistive)

For 2.2 kW asynchronous motor with compensation condition, voltage waveforms are shown in Fig. 17. Voltage levels were measured as 231.3 V, 233.8 V, and 237.1 V for L1, L2, and L3 respectively. Power factor of the system ($\cos \phi$) was measured as 0.9.

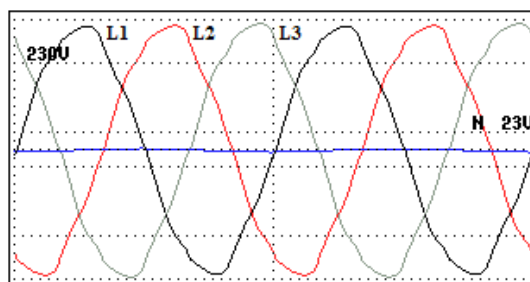


Fig.17. Voltage waveforms from system bus under compensation condition (for asynchronous motor)

In Fig. 18, current waveforms of a 2.2 kW asynchronous motor are shown. Current levels were measured by Fluke 435 as 2 A for L1, L2, and L3 respectively.

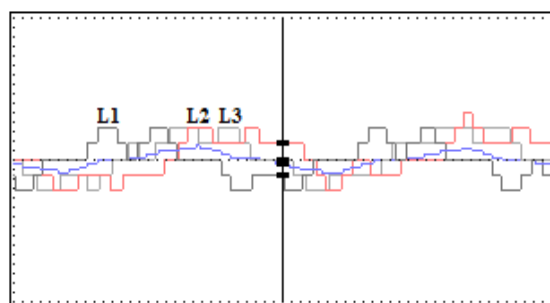


Fig.18. Current waveforms from system bus under compensation condition (for asynchronous motor)

Conclusions

In this study, a RPCU was investigated. A RPCU which has 15-kVAR capacitor group was designed and constructed. This unit has a RPCR to control capacitors automatically.

To test this unit, an inductive load, a resistive load and an asynchronous motor were used. As shown in section of experimental study, designed 15-kVAR compensation unit

was tested under different load changes. First of all, an inductive load was connected to the RPCU. Voltage, current, and harmonic signals were measured by Fluke 435 power quality analyzer. Then the other loads which are a resistive load bank and an asynchronous motor were connected to the system.

The designed system is suitable for reactive power compensation applications. It is flexible and adaptable for power systems. According to calculated power needings, capacitor groups can be added to the system. The RPCU responds the load changes within 4 or 5 seconds.

It is obviously seen that voltage waveforms are not disordered under load changes although current waveforms are affected from some loads like asynchronous motors. Measured current harmonics will be eliminated in further studies for purely inductive loads and combined loads.

The power factors of the system for different load changes were measured by Fluke 435 power quality analyzer. From those measurements, it can be said that designed RPCU increases power factor of the system. Thus the reactive power necessity is supplied by the RPCU instead of the power network for inductive loads.

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